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Dr. T. M. Shaun Johnston and Dr. Daniel R. Rudnick

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of California, San Diego
Scripps Institution of Oceanography
Climate, Atmospheric Science and Physical Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0213

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Office of Naval Research
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14. ABSTRACT

During the AESOP field program near Monterey Bay, our cruise from 29 July-28 August 2006 was divided into three segments: a frontal survey from 30 July-6 August, an offshore line to examine submesoscale decay away from the coast from 6-10 August, and an internal tide survey from 10-25 August (Fig. 1). SeaSoar was towed behind a ship at 4 m/s and made saw ›oth profiles to depths of 350-400 m. For the 2 frontal surveys we have calculated vertical velocity using the generalized omega equation including parameterizations of mixing. Statistics from offshore line will be compared to a high-resolution numerical simulation. For the tidal survey we produced a phase-averaged description of energy and mixing in a tidal beam over Monterey Canyon.

15. SUBJECT TERMS

internal tide, mixing, front, omega equation, vertical velocity

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SeaSoar and Doppler Sonar Spatial Survey of Internal Tide Generation, Surface Boundary Layer Dynamics, and Mixing

T. M. Shaun Johnston
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Dr, #0213
La Jolla, CA, 92093-0213
phone: (858) 534-9747 fax: (858) 534-8045 email: shaunj@ucsd.edu

Daniel L. Rudnick
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Dr, #0213
La Jolla, CA, 92093-0213
phone: (858) 534-7669 fax: (858) 534-8045 email: drudnick@ucsd.edu

Award Number: N00014-05-1-0333
http://www-pord.ucsd.edu/~shaunj/

LONG-TERM GOALS

The overall goal of the Assessing the Effects of Submesoscale Ocean Parameterizations (AESOP) initiative is to produce a dynamical framework to evaluate the impact of submesoscale ocean parameterizations on regional ocean model forecasts. Our observations will improve understanding of 1) internal tides and associated mixing, 2) submesoscale processes in the surface boundary layer, and 3) vertical velocity (w) and mixing at an upwelling front.

OBJECTIVES

Our objectives cover three themes: frontal dynamics, the decay of submesoscale activity away from the coast, and internal tide generation and dissipation.

- *Frontal dynamics*
  - What is the distribution of w at the front?
  - What are the main forcing terms?
  - What effect does mixing have?

- *Submesoscale decay away from the coast*
  - What is the observed statistical description (e.g., temperature gradient and vorticity probability distribution functions)?

  - How does it compare to a high-resolution regional model [Capet et al., 2008]?

- *Internal tide generation and dissipation*
  - Where is the internal tide generated in the Monterey Bay area?
  - How and where is it dissipated?
  - How well do parameterizations describe internal tide-driven mixing?

APPROACH

Overview of observations. During the AESOP field program near Monterey Bay, our cruise from 29 July-28 August 2006 was divided into three segments: a frontal survey from 30 July-6 August, an offshore line to examine submesoscale decay away from the coast from 6-10 August, and an internal tide survey from 10-25 August (Fig. 1). SeaSoar was towed behind a ship at 4 m s^{-1} and made sawtooth profiles to depths of 350-400 m. We obtained: 1) hydrography from 0-400 m at 8-m vertical and ~3-km horizontal resolution from a SeaSoar equipped with a CTD, fluorometer, oxygen sensor, and transmissometer; 2) conductivity microstructure sampled at 2048 Hz from a Transmitting Microstructure System (TMS) mounted below the SeaSoar; and 3) currents to depths of 100, 400, and 600 m at vertical resolutions of 4, 8, and 16 m using vessel-mounted acoustic Doppler current profilers (ADCP). Our measurements are of similar horizontal resolution to regional models and can be used to validate numerical model output and their parameterization schemes. Conductivity microstructure can be used to determine the Cox number, from which the thermal diffusivity (K_T) and the dissipation of temperature gradient variance (χ) can be calculated. The advantage of using the SeaSoar to obtain microstructure measurements is that a large area can be surveyed rapidly and repeatedly.

Frontal surveys. Two near-synoptic surveys were made of a mesoscale upwelling front with at least 9 crossings of the front at 11 km spacing (Fig. 2). While deepening of the mixed layer is usually described well by one-dimensional mixing models (e.g., KPP or Price-Weller-Pinkel), mixed layer restratification is more complex and involves lateral secondary circulations and strong vertical velocities. An upwelling front was observed during restratification at small-scale by Lee and D'Asaro (APL) using a neutrally-buoyant Lagrangian mixed layer float, at kilometer-scale by TriAxus, and near-synoptically over the mesoscale by SeaSoar.

Cross-shore surveys. Two surveys of ~400 km in length were made on- and offshore of Pt. Sur to examine the decay of submesoscale variability away from the coast (Fig. 1). In particular we will make statistical comparisons between our observations and a high-resolution idealized California Current System model [Capet et al., 2008]. Probability distribution functions of horizontal gradients of temperature and salinity indicate how well models resolve the observed fronts. Probability distribution functions of observed vorticity are positively skewed due to large cyclonic vorticities in the mixed layer [Rudnick 2001].

Internal tide survey. The internal tide survey repeatedly surveyed three lines extending north of Sur Platform and across Monterey Canyon to a submarine fan (Fig. 1), all of which are believed to generate internal tides [Lien and Gregg, 2001; Petruncio et al., 1998; Kunze et al., 2002]. These lines were repeated ~20 times each and at different phases of the tide (Fig. 3). Significant mesoscale variability was expected in this region, which refracts internal tides. Therefore, three adjacent lines were surveyed near R/P *FLIP*. SeaSoar measurements are valuable for their broad coverage, which complements the moored time series at *FLIP* and rapid expendable current profiles made around *FLIP*. Several AESOP models, ASAP's HOPS model, and a modified version of the Princeton Ocean Model (POM) [Carter, 2009] include tides. Model-data comparisons of internal tidal amplitudes, energy density, and fluxes are made with POM.

WORK COMPLETED

Vertical velocity at the front. Enric Pallas Sanz (postdoctoral researcher, SIO) has completed a manuscript titled ``Frontal dynamics and analysis of *w* at a front in the California Current," which will be submitted to the Journal of Physical Oceanography in November. Frontal ageostrophic circulations are large and contribute to restratification (Fig. 4). Objectively-mapped observations are fitted to dynamics via the quasigeostrophic Ω equation and the generalized Ω equation, from which we obtain the distribution of *w* and the forcing terms including the surface-intensified mixing.

Internal tide generation and dissipation. Modelled internal tidal amplitudes and phase-averaged observations (which should be mostly due to the internal tide, but include any variability with a time scale less than the survey duration) agree qualitatively (Figs. 5 and 6). Estimates of energy flux and energy density from SeaSoar data in the upper ocean are made [Martin and Rudnick, 2006; Cole et al., 2009]. We will compare observed mixing at the internal tidal beam with one-dimensional turbulence closure schemes (e.g., KPP or Mellor-Yamada) and/or dissipation parameterizations based on shear, stratification, and/or strain [Gregg, 1989; Kunze et al., 1990; MacKinnon and Gregg, 2003].

Submesoscale decay away from the coast. Work is ongoing on this topic, but to date most of our efforts have focussed on the previous two topics.

RESULTS

Frontal dynamics. *w* is difficult to measure directly, but is important for restratification and transport of biological material. For this reason, we infer *w* from the quasigeostrophic and generalized forms of the Ω equation (the latter with and without parameterization of eddy viscosity). Streamers of chlorophyll/particulates distinct from the surface chlorophyll maximum are correlated with subduction. *w* extrema of 10 m day^{-1} are found on the light side of the front in survey 1 as a combined effect of the ageostrophic frontogenesis and downfront winds [Thomas and Lee, 2005]. Survey 2 is characterized by strong ageostrophic deformation and subduction of a cold filament. The consequences of including vertical mixing in the generalized Ω equation are a <50% enhancement of *w*.

magnitude the upper ~50 m and a reduction below. This effect of vertical mixing increases with downfront winds and is sensitive to parameterizations of viscosity.

Internal tides. One or more internal tidal beams were identified by calculating velocity variance along ~60 cross-canyon sections derived from ~20 repeats of 3 lines separated by 2-4 km (Fig. 3). The beams appear to be generated at the Sur Platform, the canyon rims, and/or a submarine fan (Fig. 5). By averaging the many repeats of these lines at different phases of the tide, the signal-to-noise ratio was increased and the velocity structure of internal tidal beams and associated mixing was identified against the background of an energetic mesoscale. Along these beams, it appears K_T estimated from the microstructure data (Fig. 7) is elevated compared to background values away from the tidal ray paths (Fig. 8).

IMPACT/APPLICATIONS

When making repeat transects, our microstructure measurements from SeaSoar can be used to identify sites of enhanced mixing over a broad area at ~3-km resolution.

RELATED PROJECTS

Collaboration with other AESOP PIs is ongoing. Our results will be useful to D'Asaro and Lee's frontal survey. We will be comparing our results with Klymak (UVic) and Pinkel's (SIO) *FLIP* data. Our cross-shore statistics will be compared with Capet et al.'s [2008] simulations. We are PIs with MacKinnon (SIO) on the IWISE DRI which is investigating internal tide generation and propagation in a sheared flow. Carter (UH), Gregg (APL), and Johnston are organizing a session at Ocean Sciences 2010 titled ``Monterey Bay region: Physical processes and their impacts."

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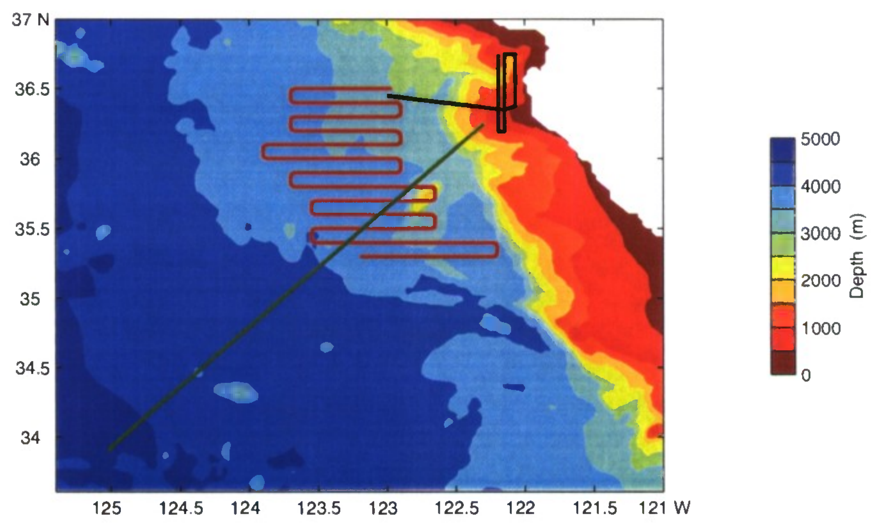

Figure 1. The nearly-synoptic survey of the upwelling front was repeated twice with many front crossings separated by 11 km (red). The offshore survey extended ~400 km offshore to document the decay of submesoscale activity. The tidal survey repeated 3 meridional lines about 20 times to cover possible refraction of the internal tide by topography or mesoscale flows.

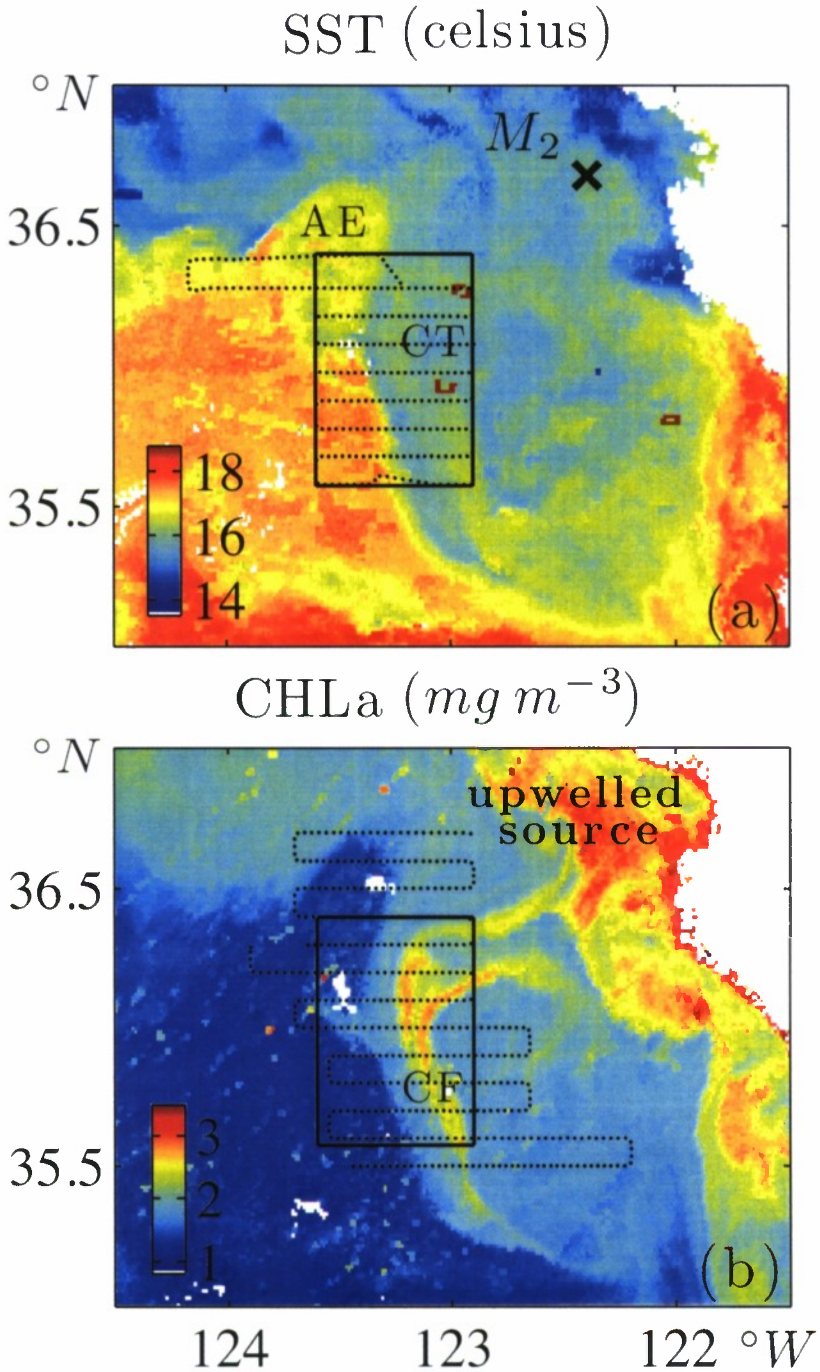

Figure 2. a) Sea surface temperature (SST) from AVHRR shows cold upwelled water near the coast and an offshore front. Cruise track from survey 1 is shown (dots). b) Sea surface chlorophyll a shows 2 streamers of chlorophyll-rich upwelled water advected along the front. Cruise track from survey 2 is shown (dots). Satellite data courtesy of NOAA Coastwatch.

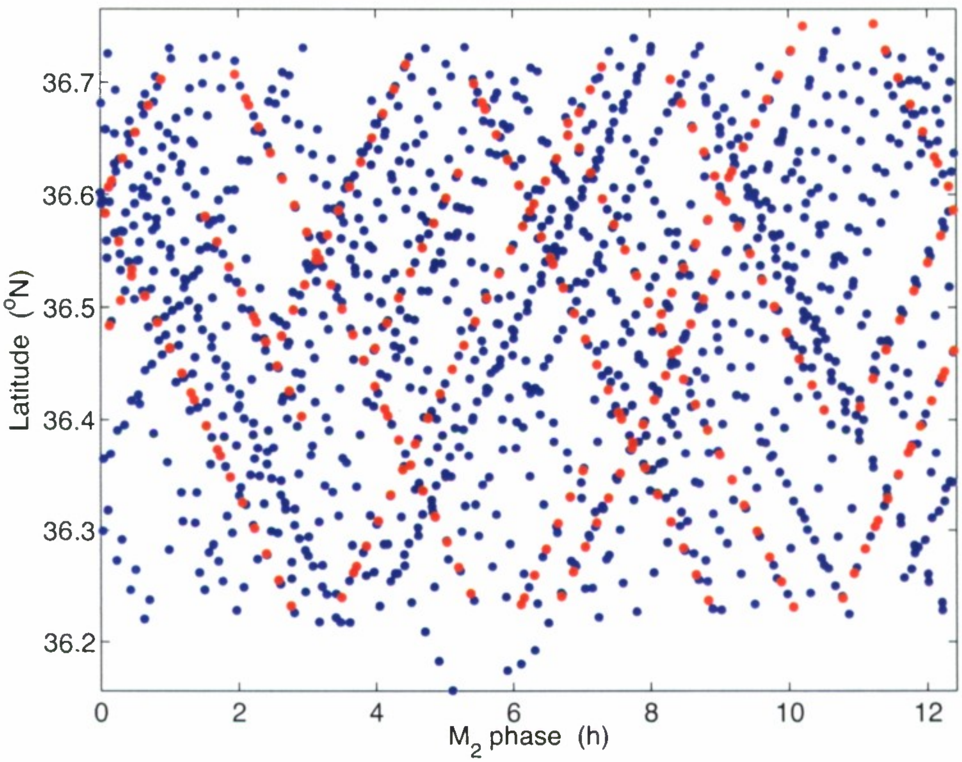

Figure 3. The tidal survey sampled each latitude of the 3 north-south lines at a different point in the tidal phase (SeaSoar data in blue, TMS data in red). Since the surveys do not resolve the tide, data are averaged across tidal phase.

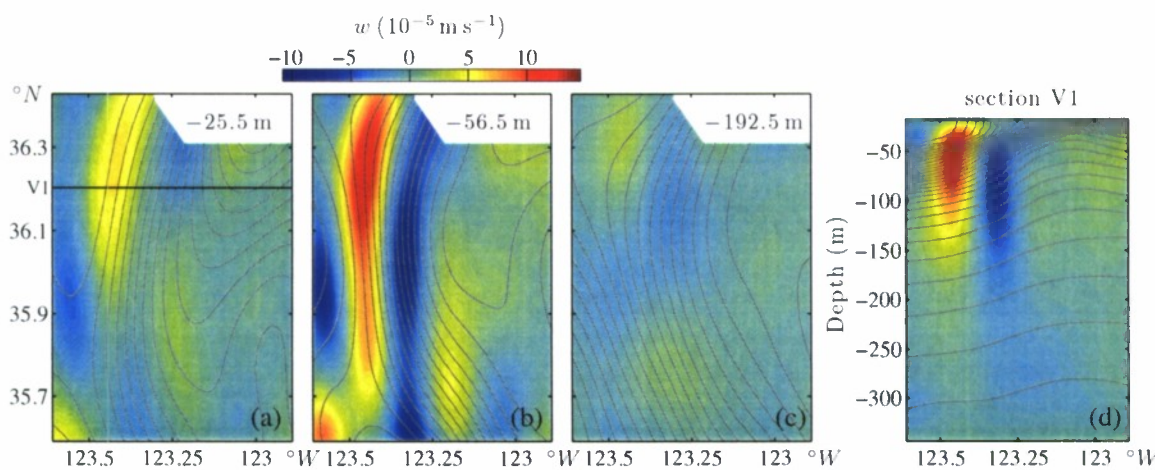

Figure 4. Vertical velocity (w) from survey 1 using the generalized Ω equation at depths of a) 25.5 m, b) 56.5 m, and c) 192.5 m. d) In a vertical slice along 36.2°N, upwelling is found on the light side, while downwelling is found underneath the sloping isopycnals of the front. The largest velocities are in the upper 150 m with velocity extrema reaching 10^{-4} m s^{-1}.

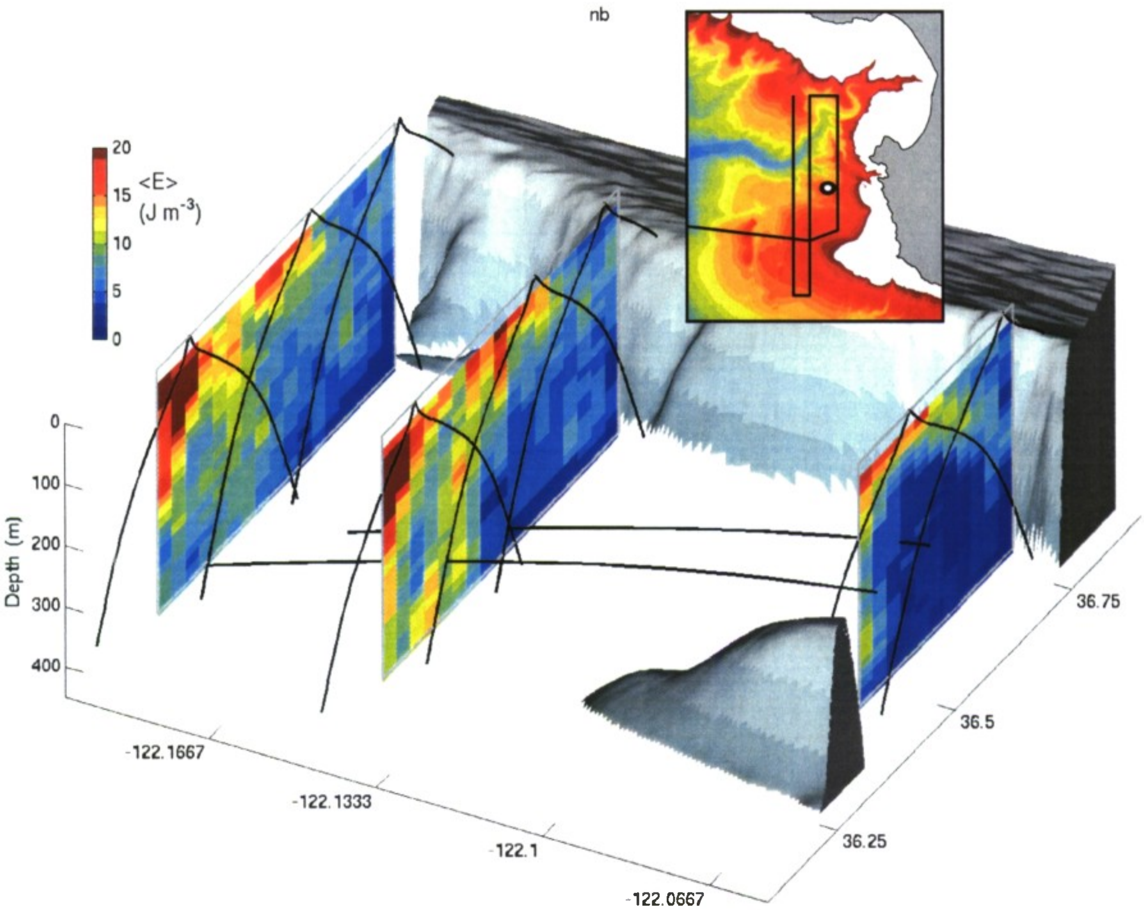

Figure 5. Velocity and displacement variance from each of the about 20 repeats of the 3 north-south sections are scaled to provide an estimate of energy density. Topography is shaded in grey at 100 m increments. Internal wave characteristics at the M2 frequency are shown (black lines). The zonal axis is elongated. Based on similar energy flux plots, in the centre section one beam appears to go upward and northward from Sur Platform, while in the eastern section another beam emanates from the north side of the canyon and goes southward and upward. The inset figure shows the location of the repeated tidal survey tracks going north from Sur Platform.

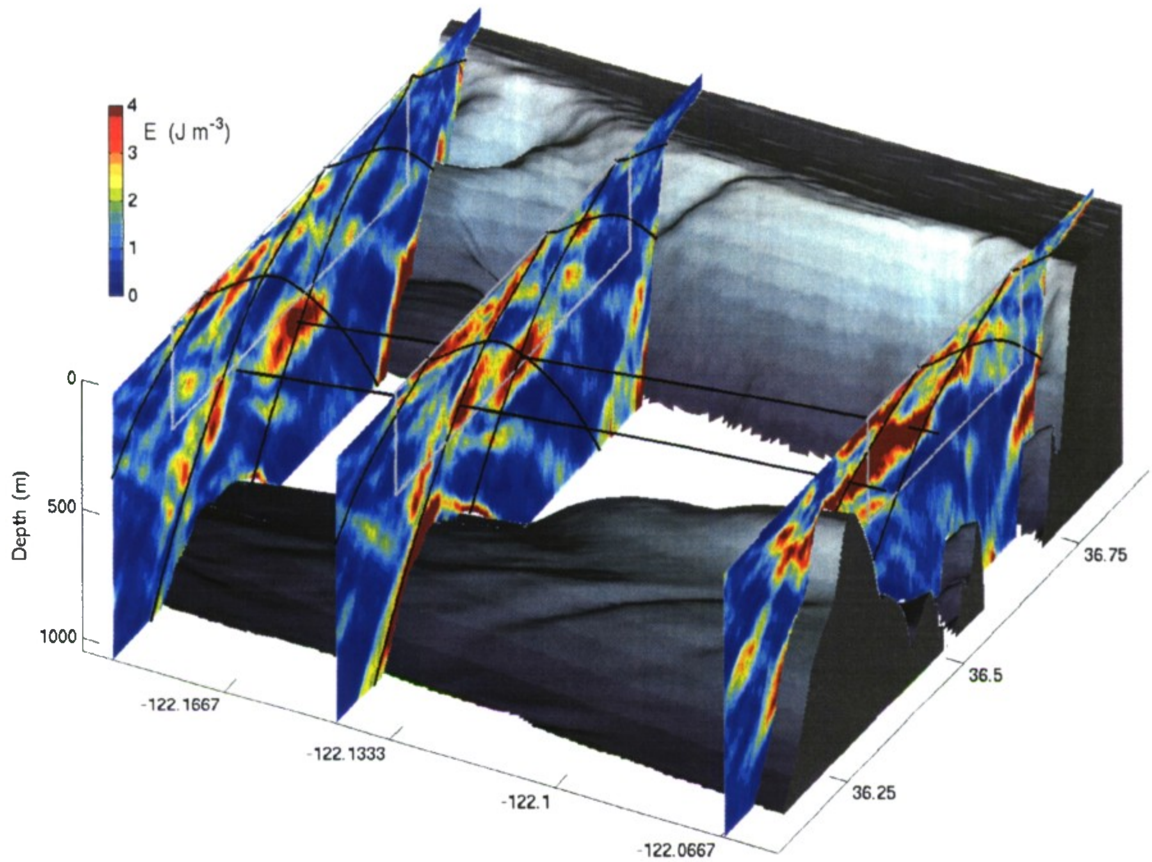

Figure 6. A more complicated pattern emerges from the model data [Carter, 2009], but the northward beam in the centre section and the southward beam in the eastern section are confirmed. Model and data show some qualitative agreement, but the magnitude of the energy density is a factor of 3 higher than in the model.

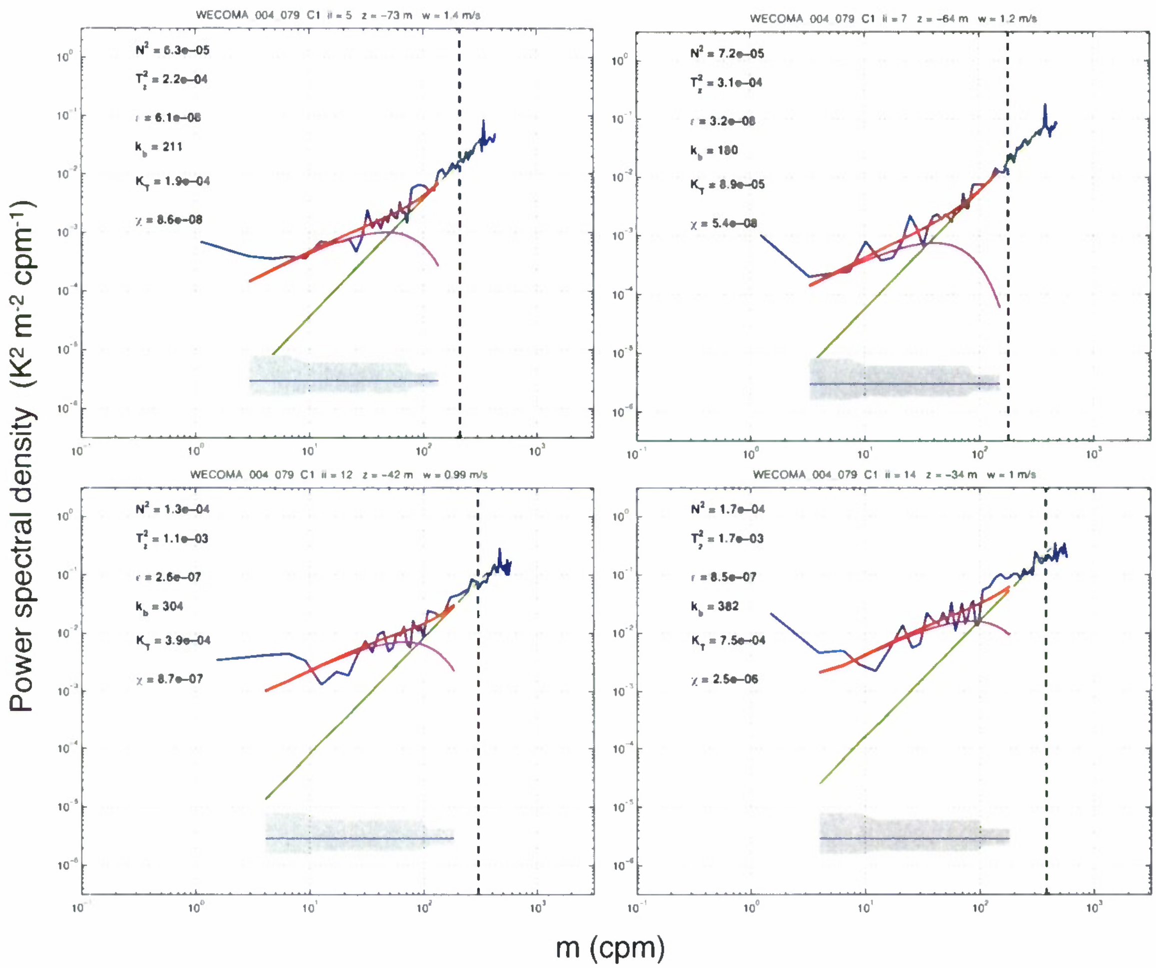

Figure 7. Microconductivity is converted to temperature and gradient spectra (blue) are fit to the sum (red) of the Batchelor spectrum (magenta) and a noise spectrum (green). The Batchelor wavenumber (black dashed line) and 95% confidence intervals (grey shading) are indicated. Four examples of these fits are shown.

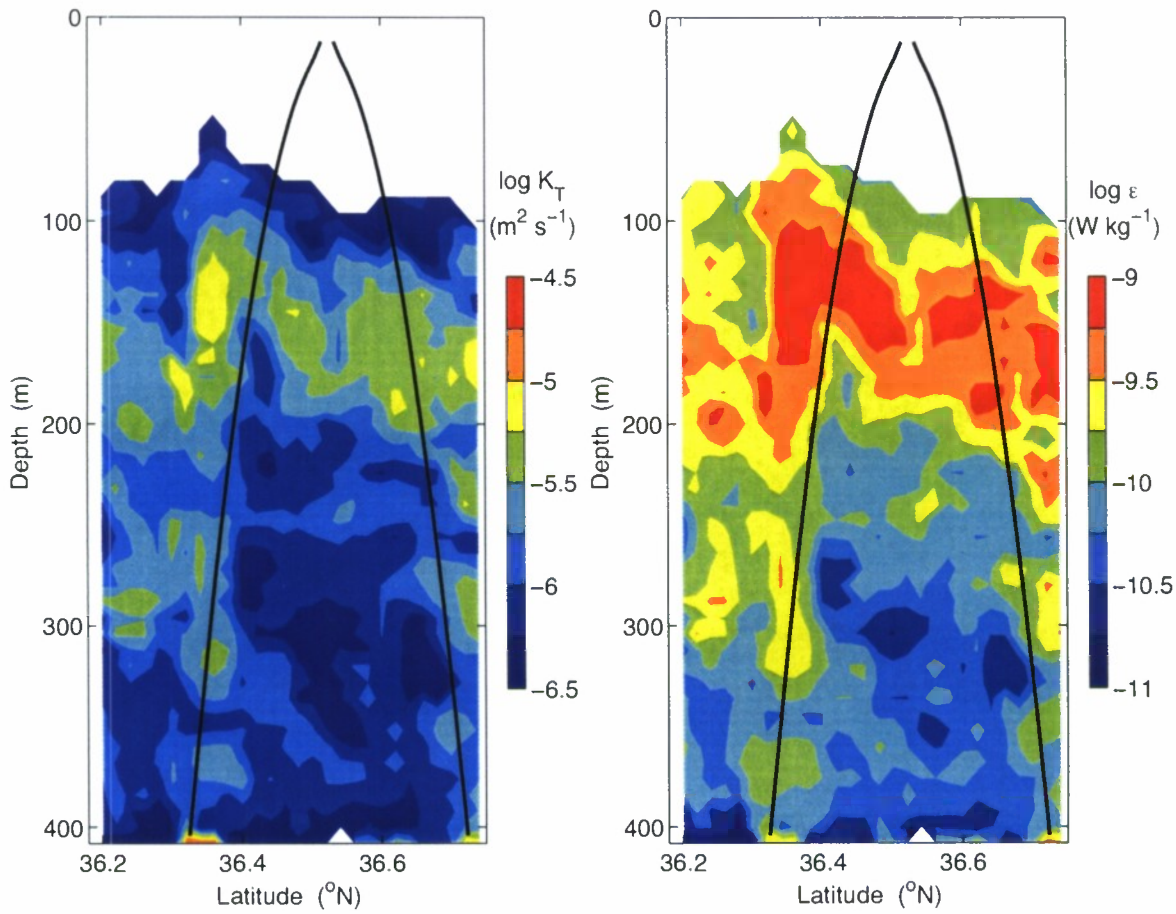

***Figure 8.** Median averaged thermal diffusivity (K_T) and turbulent dissipation (ε) are calculated from approximately 20 north-south sections of the internal tidal survey. Both are high along M_2 tidal ray paths (black lines, same as Figs. 5-6) emanating from the Sur Platform and the northern edge of the Monterey Canyon. Mixing along the ray paths appears larger, while a low diffusivities are found away from the ray paths. Measurements in the upper water column are blanked out.*